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Task Y-R011-01-015
Type B

Technical Note 475

INVESTIGATION OF MANIPULATING DEVICES FOR DEEP OCEAN EQUIPMENT

25 January 1963

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ABSTRACT

Accelerated interest in the deep ocean has focused attention on the manipulating devices to be attached to deep ocean vehicles. The object of this task is to investigate the manipulating devices that can be used in the undersea environment. The amount of work that can be accomplished by the vehicle is dependent on the agility and sophistication of its manipulating devices. The report gives details on ten manipulating systems with requirements and desirable features for manipulators included.

INTRODUCTION

There is an ever increasing need for deep ocean knowledge. Research and development is going on in the field of deep ocean vehicles and their use in construction and maintenance of deep water installations. The Laboratory desired an investigation of the manipulative devices to be attached to the deep ocean equipment. Proper selection of manipulating devices is important because the amount of work that can be accomplished by the deep ocean vehicle will be governed by them. These devices are analogous to the arms and hands of a man in the hostile environment below the practical diving limit of 275 feet.

One of the objectives of task Y-R011-01-015, Power Sources, Seals, and Special Devices for Deep Ocean Equipment, was to obtain information and investigate manipulating devices which could be adapted for deep ocean, high pressure environment. A background on manipulating devices can be obtained by studying those used for welding, forging and nuclear handling.

PREVIOUS EXPERIENCE WITH MANIPULATING DEVICES

1. Remote Underwater Manipulator (RUM), built by Scripps Institution of Oceanography, was designed for use down to depths of 20,000 feet.[1] General Mills Nuclear Equipment Department supplied an underwater version of the Model 500 Mechanical Arm for use on this vehicle. The manipulator utilizes a pressure balance system in which the interior of the manipulator is filled with oil. Provision is made for having a slight positive pressure differential between the interior and exterior of the manipulator. Then, if there is slight leakage, the oil leaks out rather than sea water leaking in. This also takes into consideration the difference in compressibility of oil and sea water. The electric motors are completely submerged in a low viscosity oil. Using a low rpm motor there is not too much loss of power because of viscous drag.

High torque hydraulic actuators cause the boom members of the manipulator to rotate. Electrically operated hydraulic servo valves control these units. The boom for the Model 500 Manipulator is capable of lifting 1000 pounds at an extension of seven feet or 100 pounds at fifteen feet. The manipulator is remotely controlled from a shore station through a multiple channel coaxial cable utilizing the multiplexing control techniques. An operator in a control van on shore views the underwater scene through four television cameras.[2]

2. The Nuclear Electronics Laboratory of Hughes Aircraft Company has made an engineering study on underwater manipulators.[3] A broad concept of these devices depicts the manipulators as extensions of human hands

in a hostile environment. The MOBOT (MObile roBOT) MARK I is a vehicle equipped with two mechanical arms. The manipulator features a modular design for versatility and economy.[4] The vehicle and manipulator are controlled by a single triaxial cable. The time-sharing multiplex control system allows for more than 100 channels of command and information data. This is accomplished through a digital, pulsating control system using synchronous commutating switches. An AC, 60 cycle system powers the vehicle and accessories and controls two closed circuit TV channels. Two cameras are required for depth perception of the underwater scene. They are mounted on movable arms to provide a flexible viewing position. The MOBOT system can be operated from a control console at a remote station such as a ship, barge or pier.

The manipulator arms have linkage much like the human arm. The manipulator, with three tubular telescoping extensions and three joints, can maneuver in all planes. Each joint can rotate $\pm 90°$ from its central position. The end of the manipulator arm has a hand which can open to six inches and can exert a 150 pound compressive force. However, such delicate objects as eggs can be handled by the versatile jaws. The hand can be rotated continuously in a clockwise or counterclockwise direction. The original design of the articulated arm specifies hydraulic control. This control system enables the arm to be locked in any position, even at full load. Operating pressure on the hydraulic system is 1000 psi above ambient pressure. The valves and actuators are enclosed in the tubular sections of the arm. Metallic parts are made of passive stainless steel, beryllium copper, or bronze to minimize corrosion.

The manipulator could be powered electrically or hydraulically. However, the hydraulic system is generally preferred for underwater applications because of quicker response as a result of less inertia of the manipulator. The response is dependent upon the weight to power ratio for the manipulator.

The vehicle used to hold the manipulators will have a rotatable turret which is supported on a square base. The mounting base will have large pressure pads on each of the corners which can be adjusted to fit the terrain. The lighting system can be incorporated in the upper turret structure that houses the manipulator and TV arms.

3. The General Electric Company has developed a remote controlled, heavy-duty manipulator for nuclear laboratory work called "Handyman."[5] It was designed with unusual strength and dexterity for use in a nuclear engineering laboratory where precise control is a requirement. It is an effective force-reflecting manipulator. An operator places his hands in a harness and performs desired motions which the slave

duplicates. The forces on the slave are fed back in some proportion to the operator so that he experiences a sensation of completing the task himself. Each slave arm is capable of lifting 75 pounds. High maneuverability is attained by having ten different modes of freedom for each arm.

"Handyman" is a pair of electrohydraulic position-error servo mechanisms. One is with the master and the other is for the slave. The force reflection can be varied from 10:1 to zero. However, it is usually kept at 3:1 so that a 75 pound load on the slave is reflected back to a 25 pound load on the operator. This bilateral response is made possible by the use of hydraulic drives with pressure feedback. Electric motors were not used because speed of response would be low. This is because of a low power to size ratio for the hydraulic system in comparison to the electric system.

4. Underwater Television Inspection and Grappling System (UTIG) is a concept of U. S. Industries for inspection and grappling to 3000 foot depths.[6] Its eight foot grappling radius allows for versatile handling of many objects through one of the following interchangeable 100 pound capacity grappling heads: jaws, magnets, suction cups, scoops, and inflatable grips. The force used to hold the object can be varied. The side of the vehicle has a storage bin with a 100 pound capacity. The vehicle is controlled through a cable from a ship by the use of a TV camera and lighting system.

5. Submerged Object Locating and Retrieving/Identification System (SOLARIS) is a vehicle built by Vitro Laboratories for the U. S. Navy.[7] It can be used down to 650 foot depths and is controlled by a surface vessel through a cable. A toggle action claw is attached to the underside of the vehicle. It is designed to clamp cylindrical objects such as nose cones, torpedoes and mines. The claw is designed to retrieve objects weighing up to 5000 pounds in water. The claw is hydraulically operated through a toggle linkage. The over-center locking action of the toggle linkage provides maximum clamping pressure while minimizing the possibility of accidental release. SOLARIS can be fitted with different claws for special tasks. A servo valve controls the hydraulic power for the claw. A fifteen horsepower electric motor drives a hydraulic pump, rated at 3000 psi, which supplies the power for all the equipment on the vehicle. A TV system is used for viewing the undersea environment.

6. A report by the Argonne National Laboratory describes an electrically connected master-slave manipulator of 30-pound capacity being used in their nuclear laboratory.[8] It has performed well and shows several advantages over mechanically connected systems. The seven

master-slave motions of the manipulators enable it to reach any point inside the cave where it operates. In order to gain mobility and force reflection, development has been carried out on master-slave manipulators which require only electrical wires between master and slave arms. The force reflection mechanism can be adjusted so that only a fraction of the force on the slave will be reflected to the operator. This diminishes operator fatigue and provides better control of heavy loads. The equipment used for adjustment of the force reflection mechanism is relatively simple compared to that when using mechanical connection between master and slave. The Model 3 Master-Slave Manipulator has master and slave arm mechanisms that are nearly identical. Force-reflection servos are used to drive the slave arm in synchronism with the motions of the master arm. These servos also reflect the load forces from the slave to the master. The usual ratio of force reflection is three to one. However, three different ratios of reflection are available.

The manipulator is capable of the following seven motions: X, Y, Z, azimuth, elevation, twist, and tong. A cable and pulley system is used as a drive for the azimuth, elevation, twist, and tong motions. Counterbalancing is achieved by mounting a weight on a parallelogram linkage for compensation of the weight of the arm.

The slave servo drive unit is composed of 4 servomotors, a synchro generator, a brake and a gearbox. A ratchet locking mechanism is used in the tong gearbox so that the tongs will hold their grip after the operator on the master unit has released his grip. Also, in case of power failure, this ratchet mechanism will still hold the tongs so that an object would not be dropped. A solenoid activates a brake lever in each of the slave gearboxes. This will lock the slave arm in the desired position. The brake, composed of a friction disk, has a capacity somewhat under the rated torque of the arm. A quick release pin allows the removal of one tong so that another can easily be inserted. The other manipulator arm is capable of performing this operation.

7. Programmed and Remote Systems Corporation builds the Model 1000 Manipulator for handling nuclear equipment up to 80 pounds in weight.[9] The motions of the manipulator available are: hand grip, wrist rotation and extension, shoulder pivot and rotation. A continuously variable velocity for each of the motions allows for a highly maneuverable manipulator. A magnetic amplifier supplies power to the electric motors which in turn drive all the components of the system. Slip clutches are used with each electric motor as a protection against overload. Wiring is internal so that snagging will be eliminated. An electric clutch controls the grip force exerted on the jaw and also

provides dynamic braking of the motor so that stopping will be smooth and quick. A variety of interchangeable jaws can be used with the manipulator.

A console unit is used for control of each motion of the manipulator. Sliding spring centered knob switches are used on the console with the velocities of the manipulator movements being proportional to the displacement of the knobs. Color coding is used for correlation between knobs and manipulator motions.

8. UNIMATE is an industrial robot built by Consolidated Controls Corporation capable of performing many types of jobs.[10] Its system with five degrees of freedom allows it to easily grasp objects. The robot is powered by high speed hydraulic servo actuators. A pressure relief valve is used with the hydraulic system so that the robot will not be overloaded. At reduced speed it can handle objects to 75 pounds with an extension up to 3-1/2 feet. For use on a deep ocean vehicle it could be modified so that a pressure balance system with oil could be used.[11] The digital memory drum can be used to relay command information through a single triaxial cable. Also, to save on weight the heavy base could be simplified because high speed is not required and the deep ocean vehicle would give adequate support. Very accurate spacial control of the manipulator is a strong feature. Presently the robot is constructed of steel and aluminum. However, for undersea use a corrosion resistant alloy could be used.

9. "Project SEAHOOK" is a proposal for a 20,000 foot manned deep-ocean vehicle by the Philco Corporation.[12] Two electro-mechanical remotely controlled manipulating arms are installed on the vehicle for performing operations such as: push, pull, turn, grip and lift. The method of control will determine the degree of dexterity to be achieved with the system. A "fail safe" mechanism is desirable so that if the arms become tangled they could be quickly removed from the vehicle. Also, this would give added buoyancy in an emergency. The operator could view the work directly through viewing ports or through a closed circuit TV system.

General Mills has made a proposal for supplying SEAHOOK with two of the Model 150 Manipulators, modified for undersea use.[13] This is the same model that has been used on the Bathyscaph Trieste. This equipment is used for nuclear handling and it can be readily adapted for undersea use. Simplicity and low cost are the major advantages of this system.

The versatile electromechanical arms are capable of working in any position with continuous operation. All motions of the arm are controlled by finger operated on-off toggle switches. The parallel jaws on the Model 150 can grasp objects up to 2-1/2 inches diameter with a 60 pound compressive force. The working radius for the manipulator is approximately

four feet. Safety features, such as slip clutches, automatic brakes, and circuit breakers are used to protect against overload. When a slip clutch is used an object can strike the manipulator arm, and the arm will slip at a given torque, thereby protecting the equipment.

Internal pressure on the manipulator is slightly greater than external pressure. This is accomplished by utilizing an oil and rubber bellows system to allow for compressibility, temperature change and slight leakage. The power for the manipulators is supplied by remotely controlled, oil immersed 24 volt DC motors. A light spindle oil of approximately 80 SUS viscosity at 100 F is used for the motor and manipulator interior because: (a) It is non-conducting (b) has a relatively low-viscosity for minimizing drag (c) has a high flash point (d) is non-toxic (e) has a relatively low compressibility and (f) past experience has shown satisfactory results. Two types of DC motors are used on the Model 150 manipulator. Three small permanent magnet motors of approximately $\frac{1}{100}$ horsepower each have been modified with special brushes for operation in an oil environment. Also used on the actuators are three DC shunt wound motors of $\frac{1}{10}$ horsepower each. These have been previously used on the RUM project. By supplying either 12 or 24 volts to the motors a two-speed system is provided because with DC motors speed is approximately proportional to supply voltage. For fine positioning the 12 volt system is used. All motions are self-locking, either by brake or irreversible gearing so that the manipulator will hold its position while under a load with the power off.

By using particular tools many specialized tasks may be performed. When the task is defined the appropriate tools can be built to fit the job. The total weight of the manipulator arms in water with oil and attaching hardware is 512 pounds.

10. The AMF Corporation has a concept for a feedback control manipulating system for SEAHOOK.[14] An inverted joy-stick with motion similar to that of the manipulator will be used for control. An advantage of this system is that the manipulator arm moves in the same direction as the joy-stick control and this allows for very good regulation with little operator training. Also, the vertical instability of the deep ocean vehicle would produce relative motion between arms and the work object and with a feedback control system this could be quickly corrected.

Design is pointed toward exceptional reliability of operation at pressures up to 15,000 psi and a range of temperature around 34 F. The system should not have any unnecessary degrees of freedom in order to avoid overcomplication of the equipment.

MANIPULATOR EXPERIENCE SUMMARY

An operator needs about 6 to 8 times as long to perform an ordinary job using the master-slave manipulator as would be required using his own hands. A switch controlled manipulator would require 5 to 10 times as long as the master-slave manipulator for performing the same job. The sense of feel and rapid response with variable speed enable the master-slave manipulator to utilize the time more efficiently. This is an important advantage for performing on the ocean bottom. The manipulator arm should be less than six feet in length because deflection of the arm under small loads would make positioning difficult. Also the viewing problems are simplified when the work is close to the vehicle. Batteries supply power for oil immersed DC motors which supply the energy for the master-slave servo system. There is magnetic coupling between the manipulator and the vehicle so that the arms can be quickly released in case of entanglement.

Each type of task to be performed by the manipulators should be investigated to find the special tools and attachments that must be used for execution of the work. The six degree of freedom system allows the manipulator to perform many operations.

REQUIREMENTS AND DESIRABLE FEATURES FOR MANIPULATORS

The requirements below are stated rather generally. More specific requirements are given in NCEL Technical Report R-204, Deep-Ocean Studies-Service Vehicle; otherwise, the information in this report should be considered. The manipulator arms will be tailored to fit the exact requirements. Two manipulating arms are to be used, so that for an operation such as tightening a bolt, the vehicle would not be twisted around because the torque used for tightening the nut with one arm will be opposed by the other arm.

Provision must be made to guard against overloading the manipulator. Devices could take the form of slip clutches, limit switches, automatic brakes, circuit breakers, or any other device which will protect the unit from overload. They should be adjusted so they would operate just under the rated torque of the arm. "Fail safe" protection should be provided by having a device such as a magnetic coupling between the manipulator and vehicle so that the arms can be quickly jettisoned in an emergency. On the console unit the toggle switch used to break the magnetic coupling should be in a remote position so there will be very little chance of accidental release of the expensive arms.

Components of the manipulating system should be selected with the following criteria in mind:

a. Galvanic action between dissimilar metals should be minimized.

b. High reliability.

c. Compact size.

d. Light weight.

e. Low power requirements.

f. Minimum corrosion

g. Resistance to motion in water

h. Performance under 10,000 psi pressure with temperature around 34 F.

A pressure balance system utilizing oil should be used so that strength and sealing problems will be minimized. Oil immersed motors with special brushes have been used as the source of power. Previous experience has proven the value of this type of system.

The manipulator will be controlled through switches or a master-slave system. Advantages of switch controlled manipulators are simplicity and economy. Also this type requires no operator attention when in a static position. Far better coordination, faster response and a "sense of feel" are the advantages gained from using a master-slave servo system. The unit may be justified if, after investigation, the working time saved would offset the greater cost and complexity. Because of temperature and compressibility effects, the deep ocean vehicles are rather unstable as to vertical motion and the master-slave system would be able to adjust to this easier than the switch controlled unit.

If a heavy duty manipulator were used to lift a massive load the unit would be bulky, slow moving and costly. Therefore, the manipulator should be less than six feet long so that it will be capable of fast and delicate manipulating. If heavy loads are to be maneuvered the manipulator can be used to guide cables and the load could be lifted by a boom.

The manipulator should have no unnecessary degrees of freedom and each pivot should be able to rotate at least $\pm 90°$ so that the manipulator will have a maximum grappling volume.

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